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S.Ashad MustufaY., John Barton, Brendan O'Flynn
Tyndall National Institute,
University College Cork,
Dyke Parade, Cork, Ireland.
{ashad.mustufa, john.barton, Brendan.oflynn}@tyndall.ie

Richard Davies, Paul McCullagh, Huiru Zheng
School of Computing and Mathematics
Ulster University
Jordanstown Co. Antrim, N. Ireland, UK
{rj.davies, pj.mccullagh, h.zheng}@ulster.ac.uk

Abstract— **In this paper, we present the design and development of a smart insole that may be used to assess long term chronic conditions that affect the elderly population such as Stroke, Dementia, Parkinson's disease, Cancer, Cardiac Disease and Diabetes. This smart insole offers the potential for evidence base rehabilitation. The ICT solution detect the plantar foot pressure in a free living context through the integration of piezo sensors, microcontroller and Bluetooth technology to empirically measure the pressure at important pressure points. The insole consists of 32 piezo sensors, 01 tri-axial accelerometers, temperature sensor and force sensor to automatically switch ON/OFF the insole. The accelerometers provide context for orientation. The design comprises two flexible PCBs encased in a padded layer, in order to protect the sensors and provide comfort to wearer.**

Keywords—Wireless sensor network; flexible sensor pcb; vital signs; microsystems; wearable technology.

I. INTRODUCTION

A rapidly aging population is a global problem, and the percentage of total population represented by older people is increasing. In 1956 11.4% of the UK total population were aged over 65 years, in 2006 this had risen to 15.7% and in 2026 it is predicted to be 20.6% [1]. This change in demographics places an extra burden on health and social care services. The provision of ICT solutions can offer support in the self-management of these conditions, an area which has been recognized as having a positive effect on a patient's quality of life.

Dysfunctional gait can occur at any age, and as a result of many illnesses and injuries. A well-functioning gait pattern is essential for maintaining independence in older adults. However, as people age, gait changes occur due to structural and functional changes of the body. Significant changes can be measured by age 65 and in most of the population by age 85 [3]. Arthritis, Stroke, Parkinson's disease, and Dementia are long term conditions that can lead to significant problems with gait [4], [5], [6]. The capability to adequately monitor walking ability is important to evaluate and guide the rehabilitation process. Falls due to locomotive impairment are a major cause of injury and stress in older people resulting in incapacity, hospitalization, and subsequent social isolation. This provides decreased quality of life for the individual and an economic burden on society. Some reports show that one-third of older people living at home have had at least one fall every year. Changes that occur in gait patterns can be used as predictors to reduce the frequency of falls, to identify diagnostic measures and finally to develop programmers for preventing such falls [7]. Such programs can target strengthening of muscle groups, which can then manifest in improved gait.

Functional walking ability can be qualitatively assessed by either observation or questionnaires. These measurements provide information on the ability of the participant to walk independently in different situations of daily life. However, subjective measures do not contain information on the quality of the gait pattern. Several quantitative methods have been proposed to assess normal and pathological gait in laboratorial environments, i.e. video-based motion capture systems, force plates, mechanical goniometers, and electromagnetic tracking systems [8]. However, these methods require dedicated floor space, expensive equipment, restrictive attachments or assessment in a biomechanics laboratory. Portable, unfettered instruments for continuous gait assessments have been proposed [9]. For example, in-shoe foot pressure measurement systems can measure temporal parameters of velocity and ground reaction forces [9], however they still have problems of high non-linearity, hysteresis and temperature dependence of electric capacitive sensors.

A recent development is the use of wearable motion sensors [10], [11], based on accelerometers and rate gyroscopes (for example, ActivPal, the Ossur patient activity monitor (PAM) [8], DynaPort MiniMod [10] and Xsense MT9 [8]). These sensor systems meet the requirements for ambulatory gait analysis. However, these types of systems are not able to provide information on the weight distribution and ground contact. Current 'state of the art' gait analysis systems based on a free living context are expensive and have been designed primarily to be used in a research or clinical setting for short recording sessions [12]. The expensive nature of these devices means that adopting this technology in the health care system would currently not be cost effective. Therefore, there is a market opportunity to offer a high quality device at a lower cost. In addition current body worn systems are bulky and have interconnecting wires between components which hinders everyday usability of the system.

In particular usability becomes vitally important when targeting older users (age 65 and over) and can affect the

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uptake of the technology and or its use on a longer term basis. These practical constraints are of equal importance to the performance and specification of the system and have yet to be addressed by current commercial systems. Practical barriers such as donning and doffing are of upmost importance particularly for Stroke patients who are restricted in terms of their mobility. Most current systems fall short on this basic requirement. The Nike+ foot pod is the exception and offers an affordable and usable solution that integrates four resistive sensors into sports footwear which is capable of recording foot pressure alongside other metrics such as acceleration. Although the technology itself is quite basic it could meet the gait monitoring requirements for those with chronic conditions. However, the software has been tailored to accommodate athletes. Additionally the software platform is not open source which makes it difficult to access the data and use the system as a research platform. Kinematix [13] specialise in recording foot pressure in a free living context with an ambulatory device called Walkinsense [14, 15]. It has a number of advantages for research including adjustable sensor location and a software platform that can be integrated into other systems; however the cost of this technology is high. The device itself has been designed with the healthy population in mind and as a result limits the usability for older cohorts specifically those with chronic conditions such as Stroke. However, the sensors are not fixed in location and move around creating issues with test repeatability. In addition the intricate wiring connecting the sensors to the external hardware is brittle and is often a point of failure.

Most of these free living systems also have a requirement to attach a small electronic device either on the ankle or on the exterior of the shoe. In addition to creating donning issues for elderly users, there is also stigma attached with wearing these devices particularly when these devices could be mistaken for security tags by the ill-informed. With advances in technology the ability to concentrate and miniaturize all of the sensing and other hardware related technology has facilitated the design and developed of smart insole technology [16][17]. Although these devices provide a useful, low cost and flexible solution they are primarily used as a research tool to complement existing and expensive structural facilities (treadmills, force platforms, in gait labs, video analysis). Commercial realization of these devices and technology still requires some exploration as the markets tend to be quite niche, such as for stroke rehabilitation and for diabetic foot care. These applications vary in the needs and requirements of their respective user groups. Veristride are planning a product release in August 2015 which aims to provide the first smart insole designed to be used with Stroke patients for the purpose of clinical monitoring and rehabilitation [18].

II. System Design Overview

In this section, we discuss the design requirements, key specifications, complete system architecture and interfacing details of the smart insole.

A. System design requirments

The overarching aim of the hardware platform is to be unobtrusive and remain hidden from the user and be embedded within the footwear as shown in *Fig 1*.

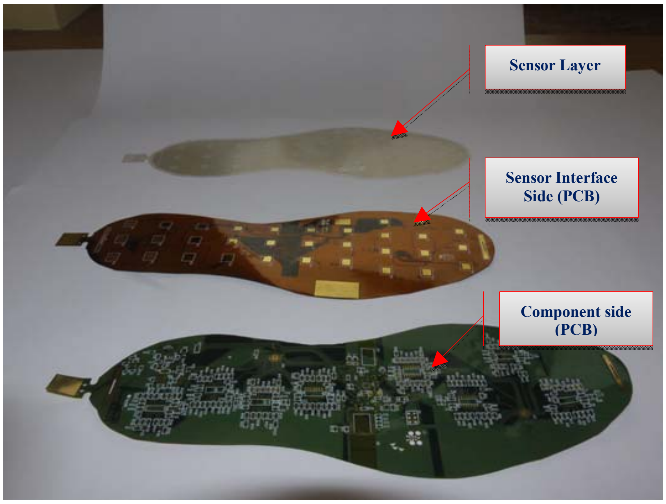

Fig 1 Flexible PCBs of sensor and interface electronic circuit.

This development introduces a hardware platform that can be incorporated within leisure footwear to allow an assessment tool in realistic living environments. The hardware platform consists of multiple layers i.e. sensor layer and hardware/ circuit layer as shown in *Fig 1*. The sensor layer is responsible for producing 32 discrete analogue pressure values from the XY plane of the insole as shown in *Fig 2*. In addition to sensing pressure the device includes an accelerometer to allow the monitoring of motion, it will allow detection of motion in 3 axis and support loads of ±6g. A third important element is the addition of a 3 axis gyroscope which is capable of monitoring the wearer's range of motion.

B. System specifications

Following is an overview specification of the smart insole, in order to meet above mentioned system design requirements.

- The smart insole consists of two sensors arrays, one per foot, each of which is integrated with a processing / communication module.
- The sensor is based upon a capacitive array which can yield a high density of sensing nodes.
- The sensors are capable of working within the pressure range of 15 kPa-1000 kPa.
- The sensitivity of the capacitive sensor is less than 0.5%. This means it should be sensitive to changes that are 0.5% of the full scale range. As the full scale range has been set to 1000 kPA the resolution of the sensor should be 5 kPA.
- The sensor array can accommodate 200 capacitive nodes which are to be arranged in a uniform pattern across the area of an insole. In order to accommodate the differences in both male and female foot sizes two distinct insole sizes are required (UK size 6 and size 9).
- The communication module uses the Bluetooth communication protocol (LMX9834) to support data transfer [19].

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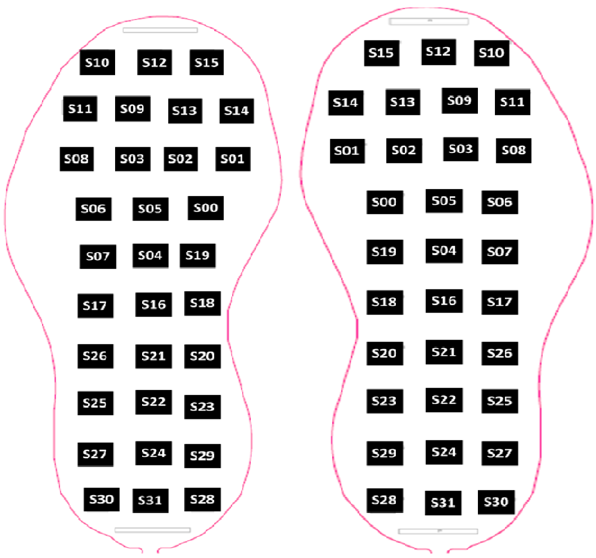

Fig 2 Placement of pressure sensing points in each smart insole.

- Data transfer is carried out in real time, with both signal stepping and continuous mode operation.
- The analogue to digital converter (ADC) resolution is 12 bits [20].
- The sampling rate of the ADC can be configurable differently in either single or continuous stepping modes. The latter sampling rate is 5Hz, which is sufficient for gait analysis.
- In addition to the capacitive pressure sensors the processing unit incorporates an accelerometer.
- The 3 axis accelerometer used in the insole can support up ±6g [21].

C. *System Architecture*

The detailed system-level block diagram of smart insole is shown in *Fig 3*. There are four critical sections in the smart insole. First section consists of pressure sensor and its signal conditioning circuits (SCC) including ADCs. In this section, 0 to 31 piezo sensors are connected to the 12 bit ADC (AD7490) through analogue SCC and the microcontroller is continuously reading the pressure sample data from ADC with the frequency of 5Hz.

The second section consists of MPU6000 inertial measurement unit (IMU). The MPU6000 gives the 3-axis accelerometer, 3-axis gyroscope and can record the ambient temperature of smart insole. This IMU sensor is used to measure the accurate information of movement and position of wearer. This is important where gait may be related to different user postures.

The third section consists of power management system including battery supervisory circuit, LDO regulators, and reference-voltage regulators for ADCs. In order to fulfill the power requirements, a 280mAh Li-ion battery is used, which is sufficient for 120 minutes of continuous operation of smart insole.

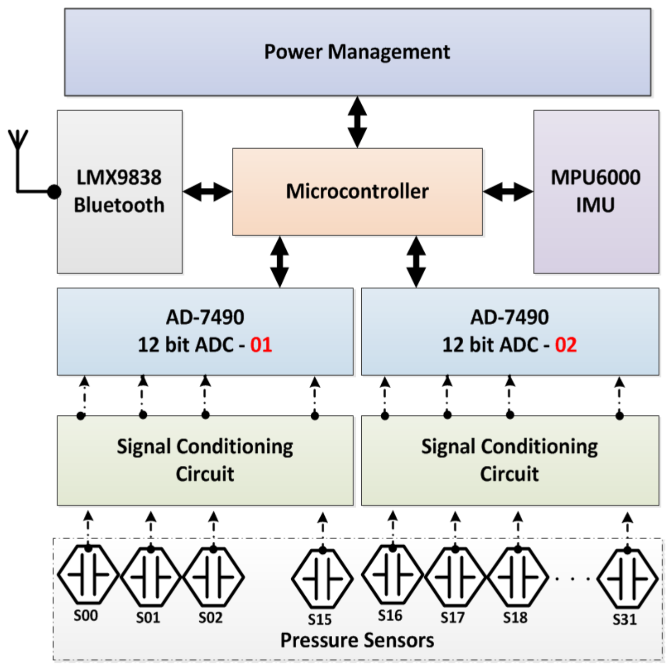

Fig 3 Complete functional block diagram of the smart insole.

The fourth section is the communication link between the Laptop/ Tablet/ Smartphone and smart insole. In the insole we used the TI LMX9838 Bluetooth chip with class II output power. During testing, we received the real-time sensor data within 3meter radius from smart insole.

The smart insole is transmitting real time sample data to the computer with a baud-rate of 115200bps. There are two configurable data transmission modes available in the smart insole.

- Single stepping mode: If smart insole is configured in single stepping mode, each time it transmits a single set of data on request and then it goes into power saving mode. The single set consists of real-time 0 to 31 pressure sensor data, 3-axis accelerometer, 3-axis gyroscope and ambient temperature data.
- Continuous stepping mode: In this mode, the smart insole starts to transmit continuously real-time sensor data stream with the frequency of 5Hz. Therefore, it can be used for 120minutes in continuous operation mode with a single recharging cycle.

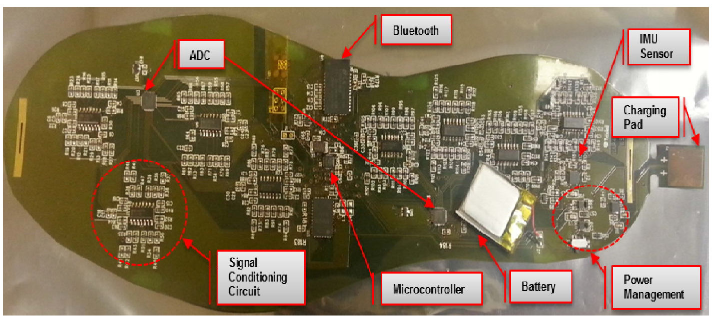

Fig 4 Placement of components on smart insole.

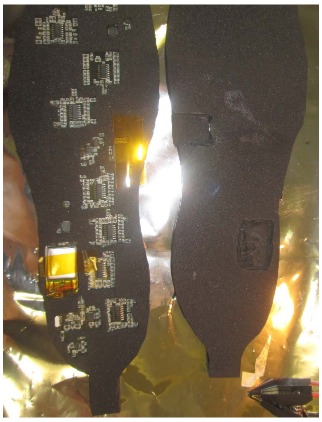

Fig 5 Packaging of smart insole.

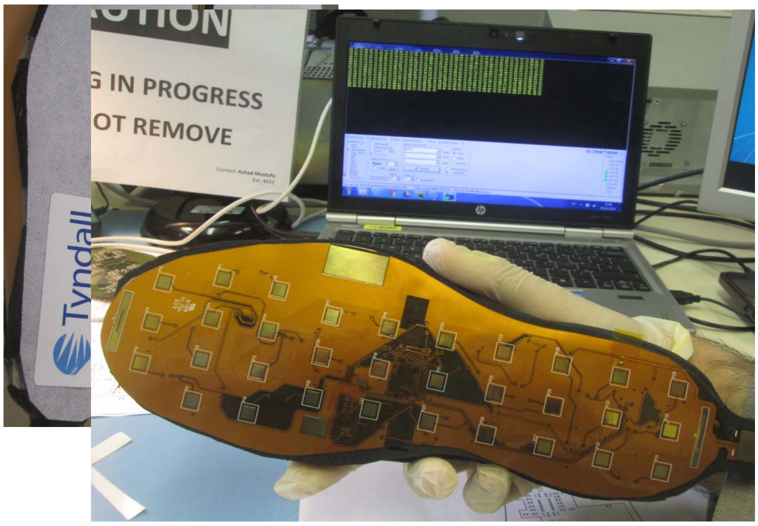

Fig 6 Testing setup for smart insole.

Fig 4 illustrates the flexible PCB with power, processing and data communication circuitry. The charging tab is shown at the right hand side of the image.

D. Packaging and System testing setup

The rugged and durable packaging is the biggest challenge we faced during implementation of the smart insole because the basic requirement of this smart insole is to fit with all types of off-the-shelf available foot wear and allow an elderly person to easily take on and off without feeling cumbersome. Therefore, we used multi-layers of soft thin foam to protect the components and sensor-layer mounted on the PCB, as shown in Fig 5.

The testing setup of smart insole is shown in Fig 6. This shows the raw sensor data stream coming from the smart insole with a baud rate of 115200bps. Then this raw data is saved in a spread-sheet for further analysis.

III. FUTURE WORK

There are a number of planned phases for subsequent development. The first phase will address the need to extend the hardware platform through a complementary software platform which will offer a set of application programming interfaces to facilitate the collection of data through a common file format. This will provide the ability to design, development and test higher order functionality such as the generation of key feature sets for subsequent gait analysis. The second phase will oversee the collection of a dataset for n=10 healthy individuals which will be used to inform the generation of a key feature set. The third and final phase will focus on the use of this technology to integrate and extend this technology into stroke rehabilitation. The aim of this research will be to identify which sub set of features are most important in the self-management of stroke rehabilitation. Additional application may include monitoring of podiatry complications associated with diabetes, assessment of performance sports such as athletics and golf, and hence the prevention of injuries due to improper gait functions.

IV. CONCLUSION

In this paper the authors present the design and development of a smart insole which provides the ability to record plantar pressure, temperature, acceleration and the rotation angle of the foot. The aim of the technology is to provide an unobtrusive and ubiquitous hardware platform that can be easily integrated into existing leisure footwear. The smart insole provides a powerful research platform that can record and subsequently perform gait analysis in a free living context which is both low cost and scalable. The smart insole uses wireless technology to facilitate data transfer which can be easily coupled with a cloud service to serve the research community.

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REFERENCES

[1] Department of Health (2004) *Improving chronic disease management.* www.dh.gov.uk/assetRoot/04/07/52/13/04075213.pdf

[2] Lugon M, Secker-Walker J (2006) *Clinical Governance in a changing NHS*, Royal Society of Medicine.

[3] Davies MJ, Dalsky GP (1997) Economy of Mobility in Older Adults, *Journal of Orthopaedic & Sports Physical Therapy* 26(2): 69-92.

[4] MR Lim, RC Huang, and A Wu *et al*. (2007) Evaluation of the Elderly Patient with an Abnormal Gait. *Journal of the American Academy of Orthopaedic Surgeons*. 15(2): 107-117.

[5] Moore ST, HG MacDougall and JM Gracies *et al.* (2007) Long-term monitoring of gait in Parkinson's disease, *Gait Posture* 26(2): 200-207.

[6] Zheng, H, Nugent, CD and McCullagh, PJ *et al.* (2010) Smart self management: assistive technology to support people with chronic disease. *Journal of Telemedicine and Telecare*, 16 (4). pp. 224-227.

[7] Serroussi RE, Gitter A et al (1996) Mechanical work adaptation of above-knee amputee ambulation. Arch Phys Med Rehabil. 77(11):1209-14.

[8] Zheng H, Black ND and Harris ND (2005) Position-sensing technologies for movement analysis in stroke rehabilitation. *Medical and Biological Engineering and Computing*, 43(4), 413-420.

[9] Lackovic I, Bilas V, Santic A and Nikolic V (2000) Measurement of gait parameters from free moving subjects, *Measurement*. 27(2):121-131.

[10] Yang, M, Zheng, H, Wang, HY, McClean, S, Hall, J and Harris, N (2012) A machine learning approach to assessing gait patterns for Complex Regional Pain Syndrome. Medical Engineering & Physics, 34 (6). pp. 740-746.

[11] Moe-Nilssen(1998) A new method for evaluating motor control in gait under real-life environmental conditions. Part 1. The instrument. *Clinical Biomechanics,* 13:320-327.

[12] Lord S, Rochester L, Baker K and Nieuwboer A (2008) Concurrent validity of accelerometry to measure gait in Parkinson disease. *Gait & Posture* 27:357-359

[13] http://www.kinematix.pt/ [Accessed 11 03 2015]

[14] Healy, A, Burgess-Walker, P, Naemi, R, Chockalingam N (2012) Repeatability of WalkinSense® in shoe pressure measurement system: A preliminary study. *The Foot*, 22: 35−39.

[15] http://www.orthomedico.eu/bco/view/en/10687033-+Walkinsense+in-shoe+pressure+measurement+.html [Accessed 11 03 2015]

[16] Xu W, Huang M-C, Amini N (2012) Smart Insole: A wearable system for gait analysis. In Proceedings of the 5th International Conference on PErvasive Technologies Related to Assistive Environments (PETRA 12), article 18, 4 pages.

[17] Xu W, Li Z, Huang M-C, Amini N and Sarrafzadeh M (2011) eCushion: An etextile device for sitting posture monitoring, In: Proc. 2011 International Conference on Body Sensor Networks (BSN 2011), pp 194-199.

[18] Redd CB, Bamberg SJM. A Wireless Sensory Feedback Device for Real-Time Gait Feedback and Training,"*Mechatronics, IEEE/ASME Transactions on*, vol.17, no.3, pp.425,433, June 2012)

[19] Texas Instruments, "TI-LMX9838 Bluetooth Serial Port", [Online]. Available http://www.ti.com/product/lmx9838. [Accessed 11 03 2015]

[20] Analog Devices, "Analog Devices," [Online]. Available: http://www.analog.com/en/products/analog-to-digital-converters/ad-converters/ad7490.html. [Accessed 11 03 2015]

[21] INVENSENSE, "MPU-6000/6050 3-AXIS GYRO, 3-AXIS ACCEL AND 9-AXIS MOTIONFUSION™", [Online]. Available: http:// http://invensense.com/mems/gyro/mpu6000.html. [Accessed 11 03 2015].